

Research Article

Geographical patterns in the distribution of naturalized plants in Central America

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Abstract

Non-native plant species are on the rise globally, yet the distribution patterns and environmental drivers in biodiversity-rich regions such as Central America remain poorly understood. These species are affecting biodiversity, ecosystem integrity, and conservation efforts, especially when they become invasive. We analyzed the spatial distribution of 751 naturalized plant species using more than 42,000 records collected through the Global Biodiversity Information Facility (GBIF) across the seven countries in Central America. We evaluated the influence of environmental variables, human population density, protected areas, and life zones on both occurrence and species richness. Human population density appeared as the strongest predictor of naturalized species occurrence and richness, highlighting the role of human activity in promoting invasions. The annual mean temperature and biodiversity integrity were negatively associated with the occurrence and species richness. Tropical rainforests and other humid life zones have more naturalized species than expected by chance. Protected areas had fewer naturalized species overall, but a higher species: observation ratio, showing both conservation value and vulnerability. Naturalized rare species, in terms of the number of records, were found outside protected zones, particularly in disturbed and urbanized areas. Our findings highlight the need for early detection, targeted management, and strengthened protection strategies, especially in mid-elevation zones and densely populated areas. By identifying key environmental and anthropogenic drivers and the most affected regions, this study offers actionable insights for conservation planning and invasive species management in one of the world's most biodiverse and socio-environmentally vulnerable regions.

Key words: Invasion patterns, invasive species, life zones, population density, protected areas

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Introduction

Naturalized plant species, those that establish self-sustaining populations outside their native range, play a complex and significant role in global change and biodiversity conservation (IPBES 2023). When naturalized species become invasive, they can severely affect ecosystem processes, economic stability, food and water security, human health, and even cultural identities (Pimentel et al. 2001; Clements et al. 2021; Heringer et al. 2021; Bacher et al. 2023). Climate, land use, economic activity, and human activity determine the diversity and abundance of naturalized plants in the geographical context (Carboni et al. 2010; Pyšek et al. 2010; Wohlgend et al. 2021; Dong et al. 2025). Understanding the drivers and distribution patterns of naturalized species is essential for developing effective management strategies to conserve biodiversity and promote ecological resilience. Although global studies have advanced invasion ecology (Carboni et al. 2010; Pyšek et al. 2010), a critical gap remains in characterizing these patterns and relationships within regions that harbor exceptionally diverse native biotas, where the impacts of invasive species may be particularly significant. Central America, with its high biodiversity and unique ecological contexts, provides an ideal setting to examine how environmental factors and human activities interact to shape naturalization patterns.

With approximately 20,000 plant species and 23% endemism (Govaerts 2024), Central America is a biodiversity hotspot (Coates 1999). However, the region also faces a high degree of ecological and socioeconomic vulnerability due to a long history of colonialism, political instability, inequality, poverty, inadequate use of its territory, and rapid unplanned urbanization (Morales-Marroquín et al. 2022). These pressures and the limited investment in scientific research result in weak conservation policies and poor regulation of activities that affect native ecosystems (Harvey et al. 2005). For instance, managing non-native invasive and naturalized species is rarely addressed in environmental laws and policies across Central American countries (Chacón-Madrigal et al. 2022). Thus, empirical research on plant invasions in the region is still scarce compared to other regions.

Recent studies have begun to address long-standing knowledge gaps in our understanding of plant invasions in Central America (see Avalos et al. 2021; Chacón-Madrigal et al. 2022; Rojas-Sandoval et al. 2023; MacVean and Zinn 2023). These efforts have provided valuable baseline data, including species inventories, introduction pathways, and invasion histories, and highlight the pressing need for more coordinated, region-wide research on plant invasions. A persistent challenge found across these studies is the lack of updated herbarium records and systematic botanical surveys focused specifically on non-native species. In an earlier work, we documented 1,228 species in the non-native flora of Central America, including 835 naturalized species and 393 casuals (Rojas-Sandoval et al. 2023). That study also showed major introduction pathways, economic uses, and country-specific patterns. However, this region still lacks fine-scale analyses of species distributions and the environmental and human factors influencing their spread. Addressing these gaps is crucial, as they limit the region's ability to develop predictive tools and proactive strategies to manage invasive species and mitigate their ecological and socioeconomic impacts.

In this study, we evaluate the distribution patterns of naturalized species across Central America with key environmental and anthropogenic factors. Specifically, we assess the distribution of these species across ecosystems classified as life zones,

protected areas versus unprotected areas, biodiversity integrity, gradients of human population density, mean annual temperature (MAT), and annual precipitation (AP). We selected these variables because they represent well-established drivers of naturalization or invasibility, supported by both theoretical and empirical evidence (Pyšek et al. 2010; Wohlgend et al. 2021). Climatic variables (MAT and AP) influence naturalized species by determining environmental suitability; we predict higher richness in warmer, wetter areas (Pyšek et al. 2010; Wohlgend et al. 2021). Human population density reflects propagule pressure and disturbance, and it is expected to be positively associated with naturalization (Lockwood et al. 2005). Biodiversity integrity, in contrast, is expected to show a negative association, consistent with the biotic resistance hypothesis (Levine et al. 2004). Finally, protection status may reduce naturalization due to lower disturbance (Bhatta et al. 2025), though mixed evidence suggests that protected areas can also be susceptible to invasions (Hiley et al. 2023). By identifying the ecological and socioeconomic drivers of naturalized species distributions in Central America, we aim to conduct future research, guide policy development, and support evidence-based management strategies. Our findings offer crucial insight into the role of protected areas in buffering against biological invasions and keeping biodiversity, as well as the vulnerability of disturbed landscapes and the potential for climatic and demographic trends to shape future invasions. This research enhances the scientific understanding of biological invasions in the tropics. It offers practical guidance for preserving the ecological integrity of diverse landscapes in a region of global conservation significance.

Methods

Study site

We analyzed all seven countries comprising Central America: Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. These countries cover a total area of 525,300 km² (World Bank 2022) and encompass a complex and diverse geography, including mountain ranges, volcanoes, plains, and significant bodies of water. Elevation ranges from sea level to 4,220 m a.s.l. at Tajumulco Volcano in Guatemala. The mean annual temperature is 24 °C, with average minimum temperatures ranging from 0 °C during the coldest month in the highlands to maximum temperatures of around 30 °C during the hottest month in the lowlands (Taylor and Alfaro 2005). Annual rainfall varies widely due to topographic and elevational gradients. For instance, El Salvador and parts of Guatemala, Honduras, and Nicaragua receive less than 1,000 mm of rainfall annually. In contrast, other regions in Guatemala, Panama, and Costa Rica receive more than 2,500 mm, reaching 5,000 mm/year in some areas of the Caribbean slope of Costa Rica and Nicaragua, as well as in the southern part of Costa Rica. The region has distinct wet and dry seasons, with the wet season typically extending from May to November (coinciding with increased hurricanes and tropical storm activity), while the dry season extends from December to April. The Caribbean coast is generally more humid and receives more rainfall than the Pacific coast (Taylor and Alfaro 2005).

Central America is a narrow land bridge connecting North America and South America, separating the Pacific Ocean from the Caribbean Sea. Its formation began 60 Ma ago and the land bridge closed the interoceanic canal between Middle and Late Miocene, ca. 13–3 million years ago (Montes et al. 2015), allowing the

movement of previously isolated biota of North and South America in an extraordinary biogeographical event (Bagley and Johnson 2014; Leigh et al. 2014). As a corridor between two major biogeographical regions, it harbors ca. 7% of the world’s plant and animal species (Greenheck 2002). Despite its rich biodiversity and abundant natural resources, the region faces significant environmental challenges. It is considered a threatened biological hotspot with high conservation priority due to habitat degradation, soil erosion, water pollution, and climate change (Harvey et al. 2005). Deforestation, primarily driven by agriculture, is a significant concern. Substantial portions of the forest have been cleared for cattle ranching, palm oil plantations, and other agricultural activities. Estimates suggest that less than 20% of the region keeps dense forest cover, and much of the remaining forest is highly fragmented or at risk of conversion (Hoang and Kanemoto 2021). The population of Central America is ca. 50 million people. The country with the highest population is Guatemala, and the smallest is Belize (Table 1). The region has a high population growth rate, along with accelerating urbanization and migration. Economically, Central America relies heavily on agriculture, with coffee, bananas, sugarcane, and other crops as key exports (Grau and Aide 2008). However, in recent years, the economy has shifted towards manufacturing and service industries, particularly in Costa Rica and Panama (Ulku and Zaourak 2021). According to the World Bank, nearly 30% of the population lives below the poverty line, with rural areas and Indigenous communities being especially vulnerable (ECLAC 2024). The region is highly vulnerable to climate change due to its geographic location, socioeconomic inequalities, agricultural dependence, low educational levels, and weak infrastructure (Castellanos et al. 2022). Expected impacts of climate change include more frequent and intense hurricanes, floods, landslides, and droughts (Hannah et al. 2017; Donatti et al. 2019), which can lead to potential loss of life, displacement, and economic disruption. Rising sea levels may threaten coastal communities and infrastructure, and growing water scarcity could further worsen food insecurity (Hagen et al. 2022).

Due to its strategic geographic position, Central America is one of the most important global trade routes (e.g., the Panama Canal). As a result, the region is undergoing rapid economic development and increased international trade (Kerf 2021), with ecological consequences including pollution, resource degradation, and overexploitation. Infrastructure expansion, such as roads, ports, and urban areas, further contributes to environmental disturbances (ECLAC 2015) and may ease the introduction and spread of non-native species.

Table 1. Geographical and socioeconomic data of the Central American countries. Land area (km²), human population (people), Gross Domestic Product 2022 (G C2019-24 DP), number of occurrence records, and naturalized plant species.

Country	Land area (km ²)	Population	GDP (Billions US\$)	Occurrences	Species
Belize	22299.42	405272	2.8305	909	138
Costa Rica	51144.33	5180829	69.244	19179	545
El Salvador	20539.22	6336392	31.989	3261	364
Guatemala	108811.24	17357886	95.003	2904	273
Honduras	112236.73	10432860	31.426	3416	283
Nicaragua	128691.43	6948392	15.65	5373	287
Panama	74530.31	4408581	76.523	7616	286

Data collection and analysis

This study builds on an open-access dataset of 1,228 non-native plant species occurring across Central America compiled by Rojas-Sandoval et al. (2023) as part of the FINCA Project, which includes a detailed account of the taxonomic composition of alien flora in this region (Flora Introduced and Naturalized in Central America: <https://finca.collaboration.uconn.edu/>). The non-native species list for each country has been generated and reviewed by botanical experts from each country who work in local herbaria or botanical gardens, using information from herbaria and local and regional treatments, including Flora Mesoamericana (<https://legacy.tropicos.org/Project/FM>), Manual de Plantas de Costa Rica ([https://legacy.tropicos.org/Project/Costa Rica](https://legacy.tropicos.org/Project/Costa%20Rica)), Flora de Nicaragua (<https://legacy.tropicos.org/Project/FN>), and Panama Checklist (<https://legacy.tropicos.org/Project/PAC>). Also, local experts added species based on their experience. However, all species included were confirmed by records containing at least one voucher specimen in a herbarium. We standardized species names using the taxonomic name resolution service website (<https://tnrs.biendata.org/>) (Boyle et al. 2013) according to World Flora Online (<http://www.worldfloraonline.org/>). We used that list to compile records for each country, sourced from the Global Biodiversity Information Facility (GBIF, <http://www.gbif.org>) and local herbarium collections (CR, USJ) (Chacón and Saborío-R 2006; Lopez 2012; MacVean and Zinn 2023). All observations are based entirely on secondary sources. As GBIF's data providers include iNaturalist (www.inaturalist.org), it contains data collected by citizen science. However, GBIF only includes observations classified as “research grade” by iNaturalist, i.e., those with taxonomic identification confirmed by two or three users and with coordinates and date in the record. In the FINCA dataset, we classified species as either casual or naturalized following Richardson et al. (2000) and Blackburn et al. (2011). We classified species as naturalized based on any of the following criteria: expert opinion for each country, information in local treatments (as mentioned above), or the number of records for each species in each country, and considered a species naturalized if the number exceeded 10 records. We selected from the original GBIF dataset only the occurrences of the species classified as naturalized. For all occurrences, we applied the workflow by Seebens and Kaplan (2022), which includes data-cleaning procedures to eliminate errors in geographic coordinates and duplicate records. Because an exotic species may be native in another country within the same region, we restricted searches to records from countries where it was listed as exotic. The species list used for each country is available in the repository <https://zenodo.org/records/16748538>.

Central America comprises only seven countries, limiting the statistical power of analyses that treat countries as the sampling units. To address this, we analyzed patterns using a grid-based approach when variables were available at comparable spatial resolutions. Additionally, we performed country-level correlation analyses to capture general patterns. Specifically, we examined correlations between the number of occurrences and species per country, as well as among three national-level variables: land area (km²), population size, and Gross Domestic Product (GDP in billions of US dollars) for the year 2022, which is the latest year with data available for all countries. We obtained country-level data from the World Bank Data (World Bank 2022, 2025). We calculate Pearson correlation coefficients using *R* software (R Development Core Team 2022).

With a grid-based approach, we use regression analyses. For independent variables, we use annual mean temperature (AMT), annual precipitation (AP), human population density (human population), and a biodiversity integrity index. Climate data (AMT and AP) at 5-minute resolution were obtained from WorldClim (Fick and Hijmans 2017). Human population density data were obtained from WorldPop Hub at 1 km resolution (<https://hub.worldpop.org/>). We obtained biodiversity integrity index data from Gassert et al. (2022) at a 1 km resolution. We resampled all datasets in a grid with a 5-minute resolution using bilinear interpolation with the *terra* package (Hijmans 2023), ensuring a uniform resolution. To construct our dependent variables, we rasterized the occurrence data of naturalized species in a grid with a 5-minute resolution, estimating both the number of naturalized species records and the number of species per cell (Both raster datasets are available in <https://zenodo.org/records/16748538>). We used a mixed-effect regression model to assess the influence of independent variables on the number of records. Latitude and longitude were included as random effects using a Matérn correlation matrix to control spatial autocorrelation. The country was included as a fixed effect. We used the *fitme* function from the *spaMM* package (Rousset and Ferdy 2014). Species richness was analyzed using a similar model, incorporating the number of records as a fixed effect. As expected, we found that the number of species per cell was dependent on the number of records. This was evaluated and verified through a regression analysis between the number of occurrences and the number of species. For both models, we used a Poisson distribution for the response variable. We generated maps of predicted records and predicted richness for each model.

To evaluate whether life zones influence the number of occurrences of naturalized species, we used a contemporary map of life zones from Elsen et al. (2021) with a resolution of 30 seconds. We calculated the number of cells with naturalized species within each life zone. We compared the number of cells expected for each life zone with a normal distribution of values estimated by randomizing 1000 times the overall number of cells with naturalized species ($n = 14,125$) across all geographical space. We counted the number of cells within each life zone each time. We plotted the density of the distribution of expected values by random and contrasted it with the observed value per life zone. We also use the *climenv* package (Tsakalos et al. 2023) to visualize species occurrences within a climatic space diagram, comparing them to the overall availability in Central America.

We obtained and joined vector shapefiles of protected areas for each Central American country (Suppl. material 3) and then rasterized at a 30-second resolution. We obtained protected area boundaries from national datasets rather than the UNEP-WCMC database, as the latter omits several protected areas known to exist in the region; national datasets provided more complete and up-to-date coverage for all countries. We calculated the number of observations and species inside and outside protected areas and determined the number of cells with naturalized species for each category (i.e., with and without protection). We compared proportions using a Chi-square test of independence with Yates's correction. We also used rarefaction analysis with Hill numbers of order 0, 1, and 2 to compare species richness between protected and unprotected cells using the *iNEXT* package (Chao et al. 2014). We chose this analysis because it is not biased by sampling effort. We conducted all the analyses in *R* (R Development Core Team 2022).

Results

We compiled 42,658 occurrence records for 751 naturalized plant species across Central America. The number of species was positively associated with the number of records (Suppl. material 1). However, records were unevenly distributed among countries; Costa Rica accounted for the highest number of species (19,179), while Belize had the fewest (909; Table 1). Neither the number of occurrence records nor the number of species per country was correlated with land area, population size, or GDP (Suppl. material 2).

At the spatial cell level, population density, AMT, and biodiversity integrity significantly explained the number of occurrence records (Table 2, Fig. 1). Cells with higher population density had more occurrences of naturalized species. In contrast, AMT and the biodiversity integrity index negatively affect the number of records (Table 2, Fig. 1). The species richness of naturalized plants is significantly influenced by population density, AMT, and the biodiversity integrity index (Table 2). Specifically, species richness increased with population density, while it decreased in areas with higher AMT and higher biodiversity integrity values (Table 2).

When analyzing life zones, we found no significant deviation from random expectations in the cells observed with naturalized species for tropical moist, tropical dry, and premontane moist forests (Figs 2, 3). In contrast, all other life zones showed a higher-than-expected number of cells with naturalized species.

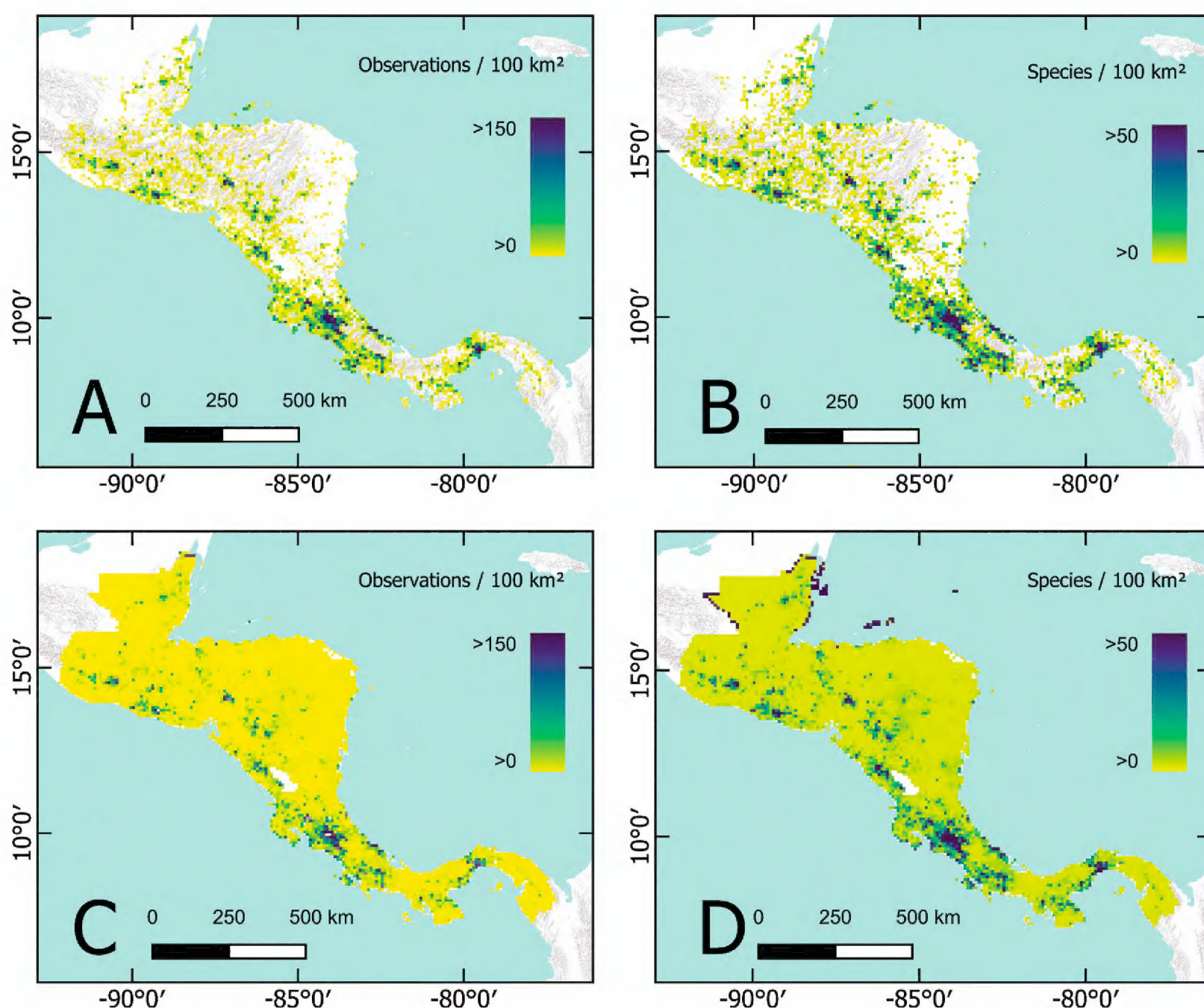


Figure 1. Maps of the number of occurrence records (A) and species richness (B) of naturalized species. Predicted number of occurrences (C) is based on population density, MAT, and biodiversity integrity, while predicted species richness (D) is based on population density, temperature, and biodiversity integrity, standardized to 300 occurrences.

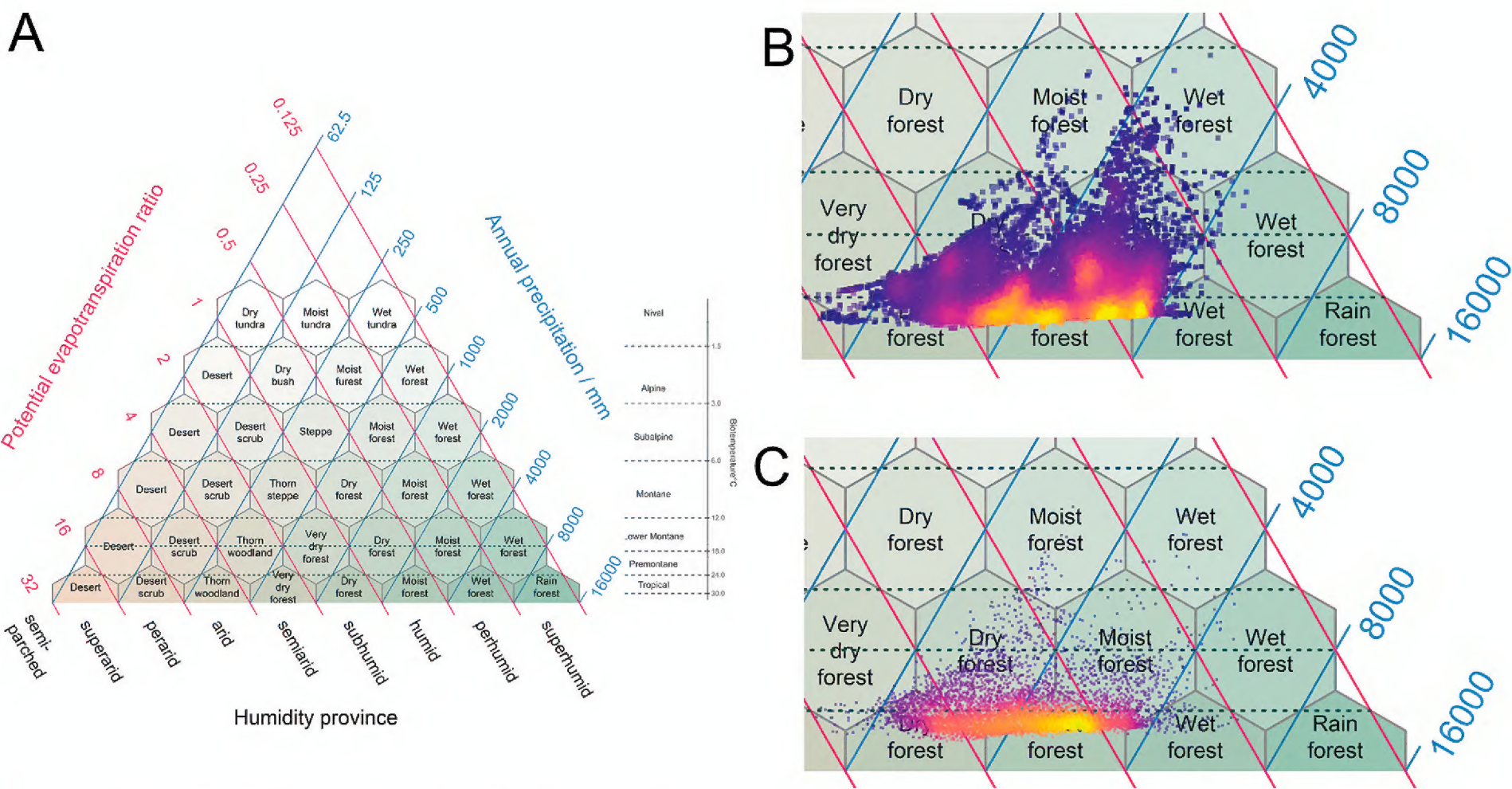


Figure 2. Holdridge life zones scheme based on biotemperature, annual precipitation, and potential evapotranspiration ratio (A). Environmental space is available within the Central American Region with (B) in the dimensions of the Holdridge life zone variables. Environmental space where naturalized species have been recorded within the dimensions of the Holdridge life zones (C). The blue points indicate low-density areas, and yellow points indicate high-density areas of species records.

Table 2. Coefficients of the mixed-effect regression model predicting the number of occurrences and the species richness of naturalized species in Central America using as predictors human population, annual mean temperature, annual precipitation, and biodiversity integrity index (see methods).

Variable	Estimate	SE	df	Chi sq. value	Pr (>F)
Number of occurrences					
(Intercept)	5.365	0.569	1	88.93	<0.001**
Population density	0.0006	0.00007	1	77.74	<0.001***
Annual mean temperature	-0.072	0.0137	1	27.882	<0.001***
Annual precipitation	0.000003	0.00009	1	0.002	0.96
Biodiversity integrity	-2.90	0.402	1	52.167	<0.001***
Species richness					
(Intercept)	4.848	0.499	1	94.28	<0.001***
Population density	0.0005	0.00006	1	66.23	<0.001***
Annual mean temperature	-0.0609	0.0121	1	25.21	<0.001***
Annual precipitation	0.000023	0.00008	1	0.085	0.77
Biodiversity integrity	-2.827	0.354	1	63.88	<0.001***

The Tropical premontane wet forest had the largest positive deviation from random expectations (Figs 2, 3), with nearly 4% more occupied cells than expected. In contrast, Tropical moist forest and Tropical dry forest had fewer cells with naturalized species than expected (Fig. 3).

On protected areas, we found 33,211 occurrences of naturalized species outside protected areas, compared to 8755 observations inside. In total, 729 naturalized species were recorded outside protected areas, while 540 were found within protected areas (Fig. 4). Most species occurring exclusively outside protected areas were seen at low frequencies (Fig. 4). No significant differences were observed in the number of common or frequent species between protected and unprotected

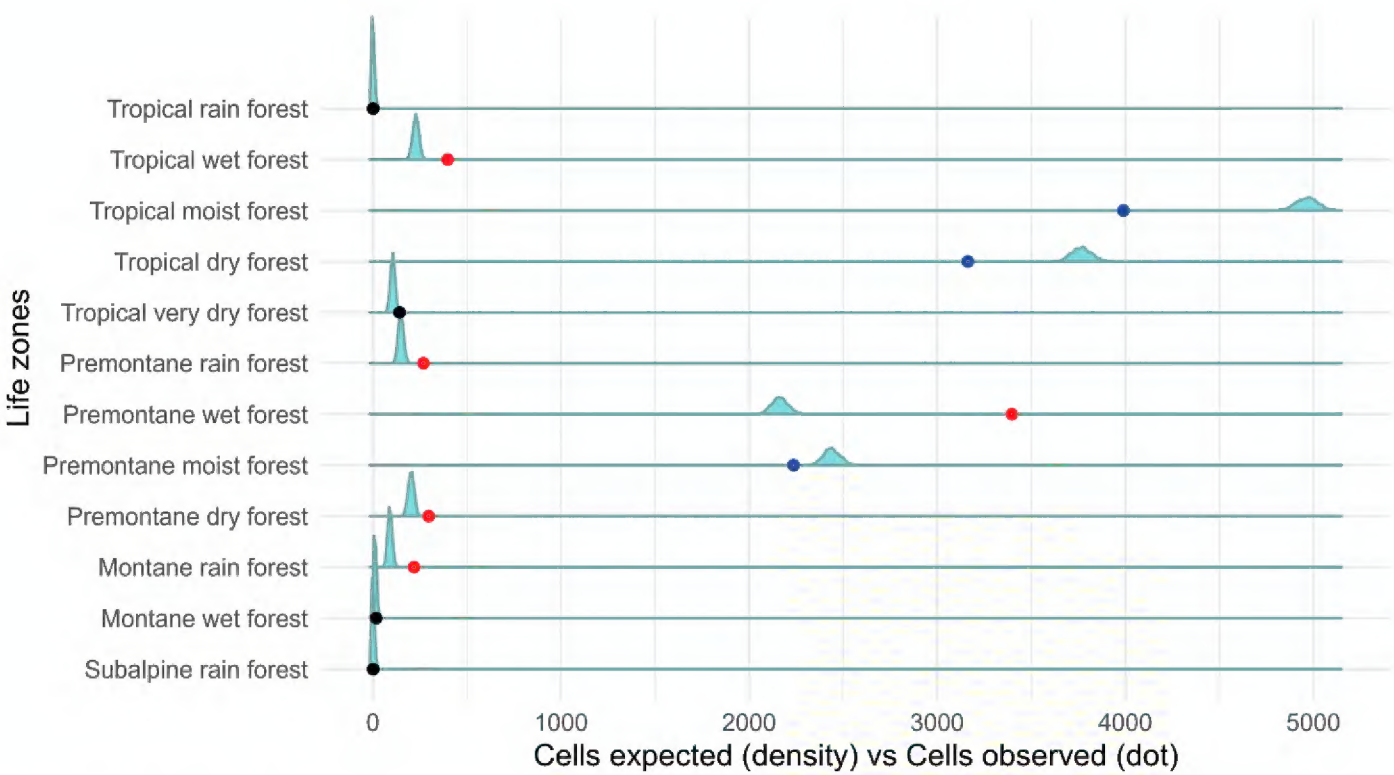


Figure 3. Observed versus expected cells with naturalized species occurrences across Holdridge life zones in Central America. Dots indicate the observed number of occupied cells, while density areas represent the expected distribution obtained by randomizing the same number of occupied cells ($n = 14,125$) 1,000 times across all life zones. Red dots indicate values higher than expected, blue dots lower than expected, and black dots values consistent with expectations.

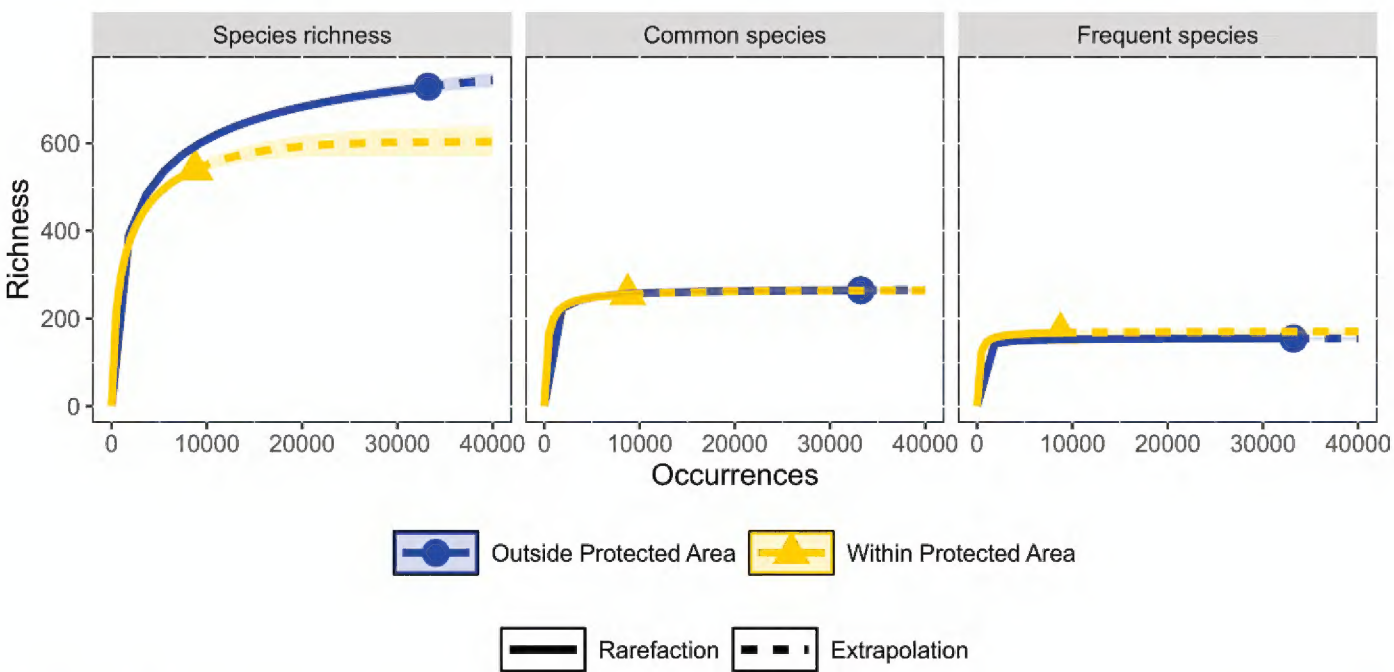


Figure 4. Rarefaction curves of the naturalized plant species in Central America occurring within and outside protected areas based on Hill's numbers 0 (species richness), 1 (common species), and 2 (frequent species). Curves represent the estimated diversity for each category, allowing a comparison of species accumulation and community structure between protected and unprotected areas. The shadow areas represent standard errors.

areas (Fig. 4). The proportion of cells with naturalized species was significantly different between protected and unprotected areas ($\chi^2 = 296$, $df = 2$, $p < 0.001$), with higher numbers of cells with naturalized species occurring outside protected areas (0.029 cells with naturalized species in unprotected areas/overall number of cells in unprotected areas) than inside (0.019 cells with naturalized species in protected areas/ overall number of cells in protected areas). However, the observation density was similar, with approximately 6.9 occurrences of naturalized species per 100 km² outside protected areas versus approximately 6.5 occurrences of naturalized species per 100 km² inside. Interestingly, the ratio of species to observations was higher within protected areas, averaging approximately six species per 100 records, compared to approximately two species per 100 records outside protected areas.

Discussion

Our findings reveal a clear pattern in the spatial distribution of naturalized plant species in Central America (Fig. 1), offering insight into future management of invasive species and the prevention of biological invasions. Among all predictors, human population density appeared as a strong determinant of both the number of occurrences and the richness of naturalized species. This is consistent with global (Essl et al. 2019) and regional studies, e.g., China (Liu et al. 2005), South Africa (Spear et al. 2013), and supports hypotheses linking invasion patterns to propagule pressure (Simberloff 2009; De Jong and Fowler 2018), disturbance (Lozon and MacIsaac 1997; González-Moreno et al. 2015), and deliberate or accidental human-mediated introductions (Zimmermann et al. 2014).

While herbarium and citizen science records are known to be spatially and temporally biased, favoring urban centers and accessible areas (Mair and Ruete 2016), our models accounted for this by including both sampling effort (number of occurrences) and country as fixed effects. Even after this correction, population density remained a significant predictor, highlighting its robust association with invasion patterns. The tendency for early records of non-native species to appear near urban areas (Aikio et al. 2012) may reflect higher propagule pressure and the role of ornamental plant use in urban landscapes (Mayer et al. 2017; van Kleunen et al. 2018; Abonyo and Oduor 2025). Our rarefaction analysis reinforces the pattern; species richness was higher outside protected areas, although there was no difference in the number of common or frequent species between protected and unprotected areas. This suggests that less frequent species are more likely to be found in disturbed, non-protected regions. Non-protected areas adjacent to or near protected zones should be prioritized for early detection and rapid response strategies to prevent the spread of potentially invasive plants into natural or protected ecosystems.

The negative association between species richness and biodiversity integrity index also supports the idea that degraded environments, often associated with human activity and high propagule pressure, are more susceptible to invasions (Marvier et al. 2004; Rojas-Sandoval and Ackerman 2021; Rojas-Sandoval et al. 2024). Additionally, differences in protection type, year of designation, and management practices among protected areas, both within and across countries, may also contribute to variability in the occurrence of naturalized species and should be considered when interpreting these patterns.

Interestingly, regions with high population density are not necessarily of low conservation value. Many urban adjacent protected areas, such as Braulio Carrillo National Park (Costa Rica), La Tigra National Park (Honduras), and El Boquerón National Park (El Salvador), safeguard critical ecosystems and deliver essential services, including water supply, air filtering, and biodiversity protection (McDonald et al. 2008; Torres-Miranda et al. 2011; Brassard et al. 2021). Although our results show more naturalized species outside protected areas, the ratio of species per observation was higher within protected areas. The pattern could be a result of less effort but more selective collecting within protected areas. However, it also suggests that protected areas, despite higher biotic resistance, lower propagule pressure, and reduced anthropogenic disturbance, are vulnerable to biological invasions (Ackerman et al. 2017). This vulnerability could be influenced by attributes such as protection level, road presence, year of designation, size, and perimeter-to-area ratio, which can shape accessibility, edge effects, and management effectiveness. While

standardized data to evaluate these factors across Central America are currently lacking, incorporating them into future analyses will be essential for assessing the effectiveness of protected areas in mitigating invasions.

We also found that the physical environment played a role in shaping the number of occurrences and species richness of naturalized species. We found an inverse effect of MAT on the number of observations and the number of species. These findings align with broader global patterns (Essl et al. 2019). However, it is relatively contrasting with our life zone analysis because those with higher humidity and temperature, such as tropical rainforests and tropical wet forests, had more occupied cells than expected under a random distribution. This pattern likely reflects regional biogeographic conditions, as much of Central America lies within humid tropical life zones, where water availability strongly limits plant establishment (Engelbrecht et al. 2007; Ratcliffe et al. 2024). Although precipitation has impacted invasive species abundance in some regions (Ratcliffe et al. 2024), it is not a globally consistent phenomenon (Wohlgend et al. 2021). Many naturalized plants in Central America originate from tropical zones (Rojas-Sandoval et al. 2023; MacVean and Zinn, 2023), making them well-adapted to high-rainfall environments where high solar radiation increases transpiration, thereby making water availability a critical filter for plant survival. Historical colonization patterns may partially explain the weak negative relationship between temperature and species richness. During the Spanish conquest and colonial period, most villages and towns were established in mid-elevation zones in areas with climates more like those in Europe (Heckadon-Moreno 1997). As a result, plant species introduced during that time became established in these mid-elevations. These historical introduction patterns likely continue to influence the current distribution of naturalized species across the region.

Conclusions

Our study highlights the strong influence of population density on the occurrence and the spread of naturalized species in Central America. These findings underscore the need to integrate conservation strategies into urban planning, with a focus on green spaces, early detection systems, and public awareness of the risks associated with invasive species. Because densely human-populated areas support high species richness and higher occurrences of naturalized species, management strategies must balance biodiversity conservation and invasive species control. Education about the impacts and consequences of species naturalization is a cornerstone of management strategies because it can help decrease propagule pressure if populations are more conscious when using exotic species. The associations between mean annual temperature and the occurrences of naturalized plants emphasize the importance of considering climatic suitability in invasion risk assessments. Similarly, mid-elevation areas with moderate temperatures, likely reflecting ecological and historical patterns of introduction, may act as hotspots for naturalized plants and should be prioritized for targeted monitoring and management.

This study also emphasizes the importance of early detection in disturbed, non-protected areas, which are likely entry points for invasive species. We highlight the role of citizen science in early detection of naturalized species, as they provide more observations than scientists or wildlife managers do, particularly in urban centers where propagule pressure may be higher. At the same time, protected areas, especially those near urban centers, play a vital role in keeping native biodiversity and providing ecosystem services. Conservation strategies should include

strengthened protection and proactive management of these areas to ensure long-term sustainability for people and natural ecosystems.

To enhance our understanding of the geographic and ecological dynamics of plant invasions, it is essential to address sampling bias in herbarium records and to increase data collection in underrepresented or remote areas. Equally critical to the effective management of invasive species is robust education at all levels. This empowers local communities, stakeholders, and decision-makers with the knowledge and tools necessary for early detection, prevention, and control. By prioritizing educational initiatives, we establish a foundation for informed monitoring and cultivate deeper public engagement in invasive species management efforts. A holistic, multidisciplinary approach that integrates ecological research, urban planning, policy development, and, most importantly, comprehensive education is essential for effectively managing naturalized plant species and safeguarding the rich and unique biodiversity of Central America.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Conceptualization: JRS, ECM. Data curation: OL, YR, ISG, JRS, PG, RF, DRD, ECM, LFA, AM. Formal analysis: ECM. Funding acquisition: JRS, ECM. Investigation: JRS, ECM. Methodology: JRS, ECM. Project administration: ECM, JRS. Resources: JRS, ECM. Software: JRS, ECM. Supervision: ECM, JRS. Validation: DRD, ISG, YR, LFA, PG, JRS, AM, RF, ECM. Visualization: ECM, JRS. Writing - original draft: JRS, ECM. Writing - review and editing: RF, PG, ECM, LFA, DRD, AM, ISG, JRS, YR.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Relationship between the number of occurrence records in the Global Biodiversity Information Facility

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Data type: tiff

Explanation note: (GBIF database and the number of naturalized plant species across Central America. Regression model: $y = 11.48 \pm 0.16 + (1,377.25 \pm 8.69) x - 233.57 \pm 8.69) \chi^2$, $df = 2868$, $p < 0.001$, $r^2 = 0.9$.

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Link: <https://doi.org/10.3897/neobiota.104.157379.suppl1>

Supplementary material 2

Correlation between the number of occurrence records of naturalized species and land surface, human population, and Gross Domestic Product (GDP) across Central American countries

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Data type: tif

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Supplementary material 3

Sources of layers of Protected Areas for each Central American country used in the analysis

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